4. Multi-channel Optical Systems

Optical Communication Systems and Networks
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Introduction to multichannel systems

- Development of new multichannel systems in order to exploit the enormous capacity provided by the optical medium
  - Several multiplexing techniques have been proposed for this purpose

ELECTRONIC MULTIPLEX – OPTICAL MEDIUM
- **ETDM**: Electronic Time Domain Multiplexing
- **SCM**: Sub-Carrier (division) Multiplexing (frequency division multiplexing)

OPTICAL MULTIPLEX – OPTICAL MEDIUM
- **OTDM**: Optical Time Division Multiplexing
- **WDM**: Wavelength Division Multiplexing (frequency division multiplexing)
Optical Time Division Multiplexing (OTDM)

- Since the 1st Generation of Optical Networks it has been extensively transmitted only one optical channel conveying multiple electrical channels multiplexed in the time domain.

- **Problem:** It is difficult to achieve bit rates higher than 10 Gb/s due to “technological limitations” both electrical components and the limitation imposed by directly modulated lasers.

- **Solution:** Optical Time Division Multiplexing (OTDM)
  - Nowadays, it is still in a research/lab stage.
  - It has not been commercially deployed yet, but it is expected to increase the bit rates per optical carrier to values higher than 1 THz.

OTDM multiplexing follows the same operation principle as ETDM multiplexing:
- Different optical pulse streams, called tributaries, originating from the same laser source, are separately encoded by electrically generated data signals.
- The aggregate channel speeds achieved are of the order of 100 - 250 Gbit/s.
Optical Time Division Multiplexing (OTDM)

Ultrafast point to point transmission system based on OTDM
Lecture 4: Multi-channel Optical Systems

Optical Communication Systems and Networks

Optical Time Division Multiplexing (OTDM)

- N digital signals in baseband modulated at $B$ bit rate uses the same optical carrier
  - They are optically multiplexed in the time domain to obtain a $N \cdot B$ b/s bit rate signal, where $N$ is the number of optical channels

- The optical transmitter in a OTDM system is a laser able to generate:
  - A periodic optical train of pulses with the same period $T_B$ as the resultant period that one channel presents at bit rate $B$
  - Pulses full-width $T_p$ must satisfy $T_p \leq (N \cdot B)^{-1}$

*Each time interval given by $T_b = B^{-1}$, the optical source emits a pulse of duration $T_p$ in such a way that $T_p \leq (N \cdot B)^{-1}*$
Optical Time Division Multiplexing (OTDM)

- The laser output is broken up into N arms leading to N independent sequences of B b/s
  - Each arm consists of a modulator and a delay line
    - The sequence of bits entering to the N arm experiments a delay given by \((N-1)/(N \cdot B)\).
    - Optical delay lines are implemented accurately by optical fiber spans: a span of 1 mm long produces a delay of \(\approx 5\, \text{ps} \) (It can be found spans even up to 10 cm)

Example: An accuracy of 0.1 ps is required to implement an optical multiplex of 40 Gb/s by delay lines of 20 \(\mu\)m.
Optical Time Division Multiplexing (OTDM)

- Unlike other multichannel techniques, OTDM requires to use a RZ coding (CRZ, in particular)

- Traditionally, NRZ coding has been asociated to the deployment of early optical systems until today

- WDM systems uses both NRZ and RZ coding, although the latter began to be used from the end of 90’s in WDM systems with dispersion management techniques

- OTDM systems require optical sources emitting a train of optical pulses of extremely short duration with rates up to 40 GHz

- Mainly, two lasers technologies have being used for this purpose:
  - **Semiconductor lasers** based on gain switching o mode locking → can provide optical pulses of 10–20 ps with a high rate even with compression ability by advanced techniques
  
  - Combination of **fiber lasers with LiNbO₃ modulators** can achieve optical pulses with ~1 ps width and rates up to 40 GHz.
1) Reception based on FWM in a nonlinear medium

- This technique takes advantage of a nonlinear effect called **FWM** (Four wave mixing), working in a similar way to the wavelength-conversion scheme.
- The **clock signal** acts also as a **pump** in the FWM process.
- Time slots in which a clock pulse overlaps with the **1 bit of the channel** that needs to be demultiplexed, FWM produces a pulse at the **new wavelength**.
- An optical filter is required to separate the demultiplexed channel from the OTDM signal and the clock signal.
Operation in OTDM systems

2) Reception based on Nonlinear Optical-Loop Mirror

- Demultiplexing is based on XPM (cross-phase modulation) nonlinear effect
- It reflects the input when the counter-propagating waves experience the same phase shift over one round trip
- The clock signal introduces a phase shift through XPM for pulses belonging to a specific channel within the OTDM signal
- The power of the optical signal and the loop length are selected to introduce a relative phase shift of $\pi$

As a result a single channel is demultiplexed
3) Reception based on MZ-type LiNbO$_3$ modulators in series

- Each modulator halves the bit rate in the incoming signal
- Different channels can be selected by changing the phase of the clock signal
- **Advantage:** This technique uses commercially available devices
- **Disadvantage:** Limited speed of modulators and overall cost when the number of channels is high (more modulators are needed)
Impairments in OTDM systems

1. In OTDM systems, transmission length is limited by **dispersion effects**: 
   - *High bit rates* ⇒ *optical pulses of short duration* (~1 ps)
2. Narrow linewidth lasers are required (DFBs)
3. It is necessary to take into consideration **polarization mode dispersion** (PMD) effects when it operates at higher bit rates and long distances
   
   → **Solution**: to use dispersion shift fibers (DSF) and/or dispersion comensation techniques

- An OTDM signal consisting of N channels at a bit rate of B b/s each equals to one channel conveying a total bit rate of NB b/s
  
  → **Example**: Typically, systems operate at bit rates of 200 Gb/s usually have a maximum reach of L<50 Km long, even operating near zero-dispersion wavelengths

- Nowadays OTDM is only in R&D:
  
  → 16 channels operating at 10 Gb/s, resulting an optical multiplex or 160 Gb/s.
  
  → Channels Mux. of 10 Gb/s to 250 Gb/s ⇒ Previous step to achieve 40 channels at 10 Gb/s by using a supercontinuum source of pulses of 1 ps duration.
  
  → 1.2 Tb/s along 70 Km by using dispersion compensation techniques

- OTDM appears as a long-term implementation technology due to the success of WDM technology nowadays
**Electrical Time Division Multiplexing (ETDM)**

N users, each one transmitting a digital signal at a bit rate of \(B\) bit/s

- Digital channel – user 1 - \(B\) bit/s
- Digital channel – user 2 - \(B\) bit/s
- Digital channel – user 3 - \(B\) bit/s
- Digital channel – user 4 - \(B\) bit/s

Aggregate channel composition with a bit rate of \(N \cdot B\) bit/s (example \(N=4\))

A broadband optical communication system transmitting an aggregate time-multiplexed signal in the electrical domain after modulating the optical source
Electrical Time Division Multiplexing (ETDM)

Features:

1. ETDM systems are based on multiplexing digital signals
2. Multiplexing and demultiplexing are always performed in electrical domain
3. Today, ETDM systems (and early WDM systems) are the most used type of multichannel systems in the backbone network
4. These systems form the core of most advanced transmission techniques:
   - Commercial systems in operation at 2.5 y 10 Gb/s
   - Commercial systems at 40 Gb/s in development and deploying process
   - Systems at 160 Gb/s in R&D process

Estructural of the electrical multiplex:

- There are several formats based on ETDM which are transmitted along optical links. These formats are mainly used in transport networks and they are based on:
  - Synchronous Digital Hierarchy (SDH/SONET), running client layers such as PDH, ATM y TCP/IP over SDH
Electrical Time Division Multiplexing (ETDM)

- **ETDM arises due to the need to provide:**
  
  a) Internationally recognized standard for the transmission of broadband signals (based on TDM)
  
  b) Platform based on the determination of channels according to their temporary location in frames transmitted synchronously
  
  c) New kinds of services in addition to voice traffic

- **Functions and properties:**
  
  a) Flexibility and scalability in terms of transmission capacity
  
  b) Implementation of robust networks and reconfigurable systems against failures
  
  c) Automation of network management functions
Impairments

- **Attenuation** effects
  - **Solution**: Using regenerators or optical amplifiers to compensate losses

- **Dispersion** (chromatic and PMD) effects
  - **Solution: dispersion management**
    - *Using dispersion compensation devices*: Dispersion compensation fibers, linear optical filters, Bragg gratings, optical-phase conjugators
    - *Applying dispersion compensation techniques*: Prechirp and new coding techniques, post-compensation techniques

- **Nonlinear** effects: *Stimulated Brillouin Scattering* and *self-phase modulation*
  - **Solution**:
    - *Keep power below threshold*
    - *Fibers with larger core cross-sections*
    - *Low levels/profile of dispersion*
Dispersion Management

Chromatic dispersion effects can be compensated:

GVD affects the optical signal through the spectral phase induced: $\exp(j\omega^2 \beta_2 z/2)$

a) Optical transmitter: avoiding chirp (external mod), reducing spectral width

b) Optical fiber: using low dispersion fibers or operating min. dispersion wavelength

c) Dispersion-Compensating Devices
   - Dispersion-Compensating Fibers (DCF)
   - Optical Filters
   - Fiber Bragg gratings
   - Optical phase conjugation

d) Dispersion-Compensating Techniques
   - Pre-compensating techniques
     – Prechirp.
     – Nonlinear prechirp
     – New coding
   - Post-compensating techniques (electrical domain)
Dispersion Management

Dispersion Compensating Fiber (DCF)

\[ E(\omega, z = L + L_{DC}) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{E}(\omega, z = 0) e^{-j\omega t} e^{j\frac{1}{2}\omega^2 (\beta_2 L + \beta_{DC} L_{DC})} d\omega \]

Perfect dispersion compensation is achieved when:
\[ \beta_2 L + \beta_{DC} L_{DC} = 0 \]
\[ or \quad DL + D_{DC} L_{DC} = 0 \]

Then, DCF length \( L_{DC} \) must be chosen to satisfy:
\[ L_{DC} = -\frac{\beta_2}{\beta_{DC}} L = -\frac{D}{D_{DC}} L \]

In general, \( L_{DC} \ll L \) since \( D \ll D_{DC} \). Typically: \(-100 < D_{DC} < -200 \text{ ps/(km.mn)}\)
Dispersion Management

Dispersion compensation maps based on DCF

Post-compensation

Pre-compensation
Dispersion Management

Dispersion management configuration. Map 1

- Dispersion management is based on the periodic dispersion compensation along the optical link by interleaving optical fibers featured with a particular dispersion profile.

- Each configuration is referred to as a dispersion map, providing a visual map of allowable dispersion variations along the link length.
Dispersion Management

Dispersion management configuration. Map 1

Dispersion management configuration. Map 2

Maximum accumulated dispersion allowable
Electrical Time Division Multiplexing (ETDM)

Dispersion compensation based on Bragg gratings

- These devices are based on the effect Bragg effect acting as selective wavelength reflective mirrors
- They are built by inserting a diffraction grating in the fiber (Bragg grating)
  - A pattern is written in the core of the fiber according to a prestablished periodic variation of the refractive index
  - When light propagates through this pattern, the wavelength satisfying Bragg condition reflects while the remaining wavelengths continue their propagation along the fiber

Bragg condition

\[ \lambda_B = 2n_0 \Lambda_B \]

Transmitted and Reflected wavelength

Refractive index profile
Dispersion Management

Optical Equalizing Filters

\[ H_{\text{fiber}}(\omega) = \exp[-j\beta(\omega)L] \]

\[ H_{\text{Compensator}}(\omega) = \frac{1}{H_{\text{fiber}}(\omega)} = \exp[j\beta(\omega)L] \]

These filters can be combined with optical amplifiers to compensate the both dispersive and loss effects (EDFA gain profile) simultaneously and periodically.

Ex: Fabry-Perot and Mach-Zehnder Interferometers
Electrical Time Division Multiplexing (ETDM)

- **Chirped Bragg gratings:**
  - Frequency chirp modulation of the refractive index of the fiber
  - Optical signals propagating through are reflected at different points depending on the distance propagated by each wavelength
Electrical Time Division Multiplexing (ETDM)

- **Optical phase conjugators (OPC):**
  - It is a nonlinear optical technique
  - It is required to obtain complex conjugated pulses by a nonlinear mixing process according to the following scheme:

  \[
  E_{in}(f) \xrightarrow{\text{OPC}} E_{out}(f)
  \]

  - **Diagram:**
    - Optical transmitter
    - OPC
    - Optical receiver
    - Nonlinear medium
    - DFG or FWM process
    - Pump laser

  Optical link to compensate:

  \[
  E_{in}(f) \quad \xrightarrow{\text{OPC}} \quad E_{out}(f)
  \]
Electrical Time Division Multiplexing (ETDM)

- **New coding techniques:**
  - Techniques based on optical carrier **frequency modulation (ASK)**
  - The FSK signal is generated by alternating two wavelengths laser (corresponding to “0” and “1” bits) spectrally separated $\Delta\lambda$
  - The delay between a “1” and a “0” depend on $\Delta\lambda$, link length and the dispersion: $\Delta T = D \cdot L \cdot \Delta\lambda$

![Diagram of ETDM](image)
Electrical Time Division Multiplexing (ETDM)

- **Post-compensation techniques**
  - They are techniques applied at the receiver
  - They are based on the equalization of dispersion effects electronically → **Heterodyne Receiver**
  - Heterodyne Receiver: converts the optical signal into a microwave signal at a *intermediate frequency* \( \omega_{IF} \), conserving amplitude and phase information.
  
- **Transfer function:**

\[
H(\omega) = e^{-[i(\omega - \omega_{IF})^2 \beta_2 L/2]}
\]

where \( \beta_2 \) is the 1st order dispersion parameter, and \( L \) is the link length
Wavelength Division Multiplexing (WDM)

How to increase the initial system capacity?

**Initial Configuration**

Bit rate per channel: \( B_i \)

\[ B_{\text{tot}} = 8 \times B_i \]

**OPTION 1**

- 8 channels
- \( B'_i > B_i \)

**OPTION 2**

- 16 channels
- \( B_i \)

**OPTION 3**

- 16 channels

### Increasing the bit rate per channel:

- **limits in electronics** and sensitivity to dispersion effect

### Increasing the number of channels:

- at the initial bit rate and keeping the bandwidth implies:
  - Arising **nonlinear effects** (FWM) and **Crosstalk** in filtering and demultiplexing

### Increasing the total spectral bandwidth:

- by increasing the number of channels at the initial bit rate and the same spectral separation. It would require **broadband optical amplifiers** (40 nm) and the arising of **nonlinear effects**
Wavelength Division Multiplexing (WDM)

Option 1: Distribution + Filtering

Option 2: Demultiplexing

Optical fiber link, with or without presence of optical amplifiers, passive optical network, point-to-point, ring, meshed, tree topology...

Data over optical carriers (optical domain)
Wavelength Division Multiplexing (WDM)

Need of increasing the available bandwidth and take advantage of the spectral band of amplification in 3rd window

Normalized wavelengths by ITU (G.691, G.694.1 and G.694.2)

Reference (anchor frequency) 193.1 THz 1552.52 nm

EDFA’s spectral band gain

Reference wavelength

\[ \Delta f = 100 \text{ GHz} \]

\( \Delta \lambda \sim 0.8 \text{ nm} \)
Wavelength Division Multiplexing (WDM)

WDM systems present the following advantages:

1) Modularity and scalability

- Create an infrastructure based on adding new optical channels to the system flexibly and according to user demands
- Service providers can reduce initial costs and progressively develop the network infrastructure
- In the design stage of optical networks, they allow to use wavelengths as a new dimension in addition to the time and space domain
- Each optical channel can increase the transmission rate at the same time other multiplexing techniques are applied
Wavelength Division Multiplexing (WDM)

2) Management and network routing functions tend to be completely performed in the optical domain, providing a great flexibility.

3) **Transparency**: Each optical channel (wavelength) can transmit signals of different rates and formats.
   - **Key issue**: The implementation of WDM and development of optical amplifiers have walked hand in hand.

   **Erbium doped fiber amplifiers** (EDFA) are optimized to work in the third window (1550 nm), presenting a gain bandwidth of 30 to 40 nm.

   Assuming a **spectral separation** between wavelengths (optical carriers) of **100 GHz (0.8 nm)**, it is possible to simultaneously amplify up to 40 channels of 10 Gbit/s, giving a total capacity of 400 Gbit/s per fiber.
Wavelength Division Multiplexing (WDM)

Impairments

Crosstalk in channel selection:
- Intra/inter crosstalk
- Frequency derives in optical sources and filters

Degradation associated to optical amplifiers:
- Accumulation of ASE noise
- Unbalanced distribution of power after amplification

Degradation by nonlinear effects:
- CPM/XPM (cross-phase modulation)
- FWM (Four-wave mixing)
- SRS (Stimulated Raman Scattering)
Losses and fiber attenuation compensation

Restrictions caused by the presence of losses can be overcome by modifying:

a) **Transmitter**: increasing the power emission
b) **Receiver**: increasing the sensibility
c) **Fiber**: using fibers with reduced attenuation coefficients or operating at spectral regions with low attenuation
d) **Introduction of amplifier stages**
   - Regenerators: one per fiber and optical carrier. **3R functions**: Reamplifying-Reshaping-Retiming
   - Optical Amplifiers (EDFAs, Raman, SOAs,...)
Attenuation and losses compensation

- Booster or power amplifier configuration
- Preamplifier configuration
- In-line amplifiers configuration
- Distribution loss compensation configuration
Impairments in WDM systems

Degradation in the channel selection: crosstalk

*Effect produced by other signal on the desired signal in optical devices such as filters, mux/demux, switches, amplifiers or optical fiber (nonlinearities)*

1) Interchannel crosstalk

- Arises when an optical device selects a channel and imperfectly rejects the others (imperfect isolation between ports)
- Occurs when the spectral separation between the desired signal’s wavelength and crosstalk signal’s wavelength (leakage) is greater than the electrical bandwidth of the receiver, unlike intrachannel crosstalk
- Can be reduced by using devices with highly isolated ports or by inserting filter stages
Impairments in WDM systems

2) Intrachannel crosstalk

- Occurs when the spectral separation between the desired signal’s wavelength and crosstalk signal’s wavelength (leakage) lies inside the electrical bandwidth of the receiver, unlike interchannel crosstalk.

- Must be considered during the channel spacing calculation in the design stage.

Example 1: Intrachannel crosstalk produced by optical switching

Example 2: Intrachannel crosstalk produced by Mux/Demultiplexing
Nonlinear Optical Effects

The response of optical fiber to light becomes nonlinear when intense electromagnetic fields propagates through

Arising effects can be:

1) Caused by the interaction of light waves with phonons (molecular vibrations)
   - **SBS, Stimulated Brillouin Scattering**
   - **SRS, Stimulated Raman Scattering**
   
   *Energy gets transferred from one optical wave to another wave at a longer wavelength (lower energy) ad it is characterized by a gain coefficient*

2) Caused by the dependence of the refractive index on the intensiy of the electric field
   - **SPM, Self-phase modulation**
   - **CPM, Cross-phase modulation**
   - **FWM, Four-wave mixing**
Effective interaction length and effective core area

**Effective length**: Length over which the impact produced by the nonlinear degrading effects are considered constant

\[ P(z) = P_0 \exp(-\alpha z) \]

\[ P_0 L_{ef} = \int_{z=0}^{L} P(z) \, dz \]

\[ L_{ef} = \frac{1 - \exp(-\alpha L)}{\alpha} \]

**Effective core area**: Cross-sectional area estimation over which fundamental mode power distribution \( F(r, \theta) \) remains constant

\[ A_{ef} = \frac{\left( \int_{r} \int_{\theta} |F(r, \theta)|^2 r \, dr \, d\theta \right)^2}{\int_{r} \int_{\theta} |F(r, \theta)|^4 r \, dr \, d\theta} \]
Stimulated Brillouin Scattering, SBS

- Interaction with phonons producing the optical signal scattering
  - Energy transfer from a high frequency wave (signal) to a low frequency wave (backward-propagating Stokes wave) over the Brillouin’s spectral band ($\Delta f_B$)
  - Effect modeled by a gain coefficient $g_B$ (typically $g_B \approx 4 \cdot 10^{-11} \text{m/W}$) and a spectral width $\Delta f_B \approx 20 \text{ MHz}$ where the interaction takes place

- SBS becomes a significative effect when the power threshold is overcome:

\[
P_{\text{SBS,threshold}} \approx \frac{21A_{ef}}{L_{ef}g_B} \quad \text{Continuous Wave}
\]
\[
P_{\text{SBS,threshold}} \approx \frac{42A_{ef}}{L_{ef}g_B} \left( 1 + \frac{\Delta f}{\Delta f_B} \right) \quad \text{NRZ modulated carrier}
\]

- SBS limits the maximum power injected into the optical fiber
  - Typical values in monochromatic source systems 10-20 mW
- Pump wave (injected signal) and Stokes wave (reflected or scattered wave) propagate in opposite directions

- SBS produces the depletion of the transmitted signal and a potentially strong reflected wave (should be blocked by isolators)
Stimulated Raman Scattering, SRS

- **Relevant features** for practical purposes:
  - High level of incident power (pump wave) induces the arising of molecular vibrations (phonons) in the silica medium.
  - Incident wave experiments **scattering** in propagating and backpropagating direction, giving part of the propagating energy to vibrational modes.
    
    In single-mode fibers SRS is mainly produced in the propagation direction (unlike SBS, it takes place in the opposite direction to the signal propagation).

- In **WDM** systems:
  - SRS causes a **power transfer** from the lower-wavelength channels to the higher wavelength channels when multiple wavelengths are injected into the fiber.
  - Then higher wavelengths get amplified SRS amplifies wavelengths (channels) placed at higher wavelengths → It is also used for amplification: **Raman Amplifiers**
Stimulated Raman Scattering, SRS

- SRS arises when propagating channels lies in its effective bandwidth and the SRS threshold is overcome. The SBS threshold is experimentally estimated by:

\[
P_{SRS}^{\text{threshold}} \approx \frac{16A_{ef}}{L_{ef}g_R(\lambda)}
\]

with \( A_{ef} \approx \pi \omega^2 \) (\( \omega \) modal field radius)

- SRS phenomenon produces an optical gain in the medium

- Raman gain coefficient \( g_R \)
  - Depends on the spectral separation among channels (wavelengths)
  - Grows near-linearly up to its peack \( g_{R_{\text{max}}} \approx 7 \cdot 10^{-14} \) m/W around 13 THz (spectral separation), falling steeply at higher frequencies

- Considered as a wide spectral effect (~125 nm or 15 THz) unlike SBS effect (~20 MHz)
  - Channels separated up to 125 nm can be coupled and experiment effects of SRS
  - The coupling occurs in both directions, unlike SBS in standard single-mode fibers which is produced only in the propagation direction
Stimulated Raman Scattering, SRS

- To evaluate the SRS effect, the Raman gain is approximated by a triangular function which depends on the channel separation $\Delta \lambda$ (optical carriers)

$$g_R(\Delta \lambda) = \begin{cases} 
  g_R \frac{\Delta \lambda}{\Delta \lambda_c}, & 0 \leq \Delta \lambda \leq \Delta \lambda_c \\
  0, & \text{in other cases}
\end{cases}$$

where $\Delta \lambda_c$ = 125 nm (15 THz), and $g_R \approx 7 \cdot 10^{-14}$ m/W at 1.55 $\mu$m is the peak gain coefficient.
Nonlinear Phase Modulation

Propagation of high optical intensities can modify the linear behaviour of the refractive index as result of anharmonic responses to intense fields:

\[ n(E) = n_0 + n_2 E^2 \]

with \( n_2 = 3.10^{-8} \text{(mm)}^2/\text{W} \), and \( E^2(t) \propto I(t) = P(t)/A_{ef} \)

\[ n(t) = n_0 + n_2 I(t) = n_0 + n_2 P(t)/A_{ef} \]

where \( n_0 \) is the linear refractive index, \( n_2 \) is the nonlinear-index coefficient, \( P \) is the optical power and \( A_{ef} \) is the effective area.

This effect produces the propagation constant dependence on the injected power

\[ \beta' = \beta + \frac{k_0 n_2 P}{A_{ef}} \equiv \beta + \gamma P \]

with \( \gamma \) nonlinear phase parameter. Typical values ranges from 1 to 5 \( W^{-1}/\text{km} \)

This behaviour leads to **self** and **cross phase modulation** in long fiber length optical systems (SPM and CPM)
Nonlinear Phase Modulation

• SELF-PHASE MODULATION

\[ \phi_{SPM} = \int_0^L (\beta' - \beta) \, dz = \int_0^L \gamma P(z) \, dz = \gamma P L_{ef} \]

Phase shift \( \phi_{SPM} \) linearly grows with the distance (effective length, \( L_{ef} \)) and injected power \( P \).

• CROSS-PHASE MODULATION

\[ \phi_{CPM} = \gamma L_{ef} \left( P_j + 2 \sum_{m \neq j} P_m \right) \]

Phase shift \( \phi_{CPM} \) for the \( j \) channel collects the SPM and the effect caused by the power of other channels transmitted simultaneously (WDM) inside the fiber.

In both cases, the overall effect contributes to increase the dispersion induced-broadening of optical pulses (depending on normal or anomalous dispersion regime)
Four-Wave Mixing, FWM

- In multichannel optical systems (WDM) several optical carriers are transmitted simultaneously at $f_1, f_2, ... f_n$ frequencies.
- The increase of injected power into the fiber leads to the dependence of the refractive index on the optical intensity propagated. This induces not only phase shifts but also new waves as a result of the combination of 2 or 3 waves: $2f_i-f_j$ (degenerated case) and $f_i+f_j-f_k$ (non-degenerated case).
- New waves can fall on desired signals causing intrachannel crosstalk.

FWM depends on:

- Number of channels
- Channel spacing número de canales
- Dispersion (fiber type)
Four-Wave Mixing, FWM

Three-frequency beating

\[ f_{ijk} = f_i + f_j - f_k \]

Two-frequency beating: Degenerated case \( i=j \)

\[ f_{jk} = 2f_j - f_k \]

Representation of generated FWM waves

M: Number of FWM components generated from the N-channel interaction of a WDM signal

\[ M = \frac{1}{2} (N^3 - N^2) \]

Example:

- \( N=2 \) -----> \( M=2 \)
- \( N=3 \) -----> \( M=9 \)
- \( N=4 \) -----> \( M=24 \)
- \( N=8 \) -----> \( M=224 \)
An increase of the frequency spacing or the presence of local chromatic dispersion can reduce the efficiency of FWM since they contribute to avoid reaching the phase matching between the interacting waves.
Four-Wave Mixing, FWM

6 equally spaced channel WDM

Optical power uniformly distributed

Input optical spectrum

Output optical spectrum

6 unequally spaced channel WDM

Input optical spectrum

Output optical spectrum

↑ Interfering beats (crosstalk)

↑ Non-interfering beats

Interfering beats (crosstalk)
Four-Wave Mixing, FWM

When channels are equally spaced in frequency in a WDM signal:

- Most of FWM components fall on desired channels causing intrachannel crosstalk
- Mean power of the WDM signal is reduced as a result of the energy transfer from interacting (desired) channels
- The combination of two previous effects leads to an unbalanced power distribution of the WDM signal

Interfering beats (crosstalk)
Non-interfering beats
Four-Wave Mixing, FWM

Intrachannel crosstalk caused by FWM can be mitigated easily by:

- Using dispersion management techniques and low dispersion fibers (Non-zero or flatted dispersion fibers) \( \rightarrow \) reduce FWM efficiency

- Unequal channel spacing in frequency domain \( \rightarrow \) In this way:
  - Interfering channels do not fall within the channel bandwidths
  - An overall power reduction is produced

\[ \text{Interfering beats (crosstalk)} \]
\[ \text{Non-interfering beats} \]
Problem: Design case

Consider the practical implementation of a single-channel digital optical system supporting SDH traffic, which operates at 1550 nm with NRZ coding and 1 GHz bandwidth to interconnect two regional data centres set 200 km apart. For this purpose, narrow linewidth DFB lasers of 1 mW power and PIN photodetectors of –30 dBm sensitivity (responsivity) are available.

- Prove the need of using a single amplifier stage in a in-line amplifier configuration to compensate losses introduced in a optical link based on a standard single mode fiber SMF 9/125. If so, determine the amplifier gain range should present. Also consider the possibility of using a booster configuration.
Parameters

\begin{align*}
\lambda &= 1550 \text{ nm} \\
P_{\text{tx}} &= 1 \text{ mW} = 0 \text{ dBm} \\
S &= -30 \text{ dBm} \\
\text{Cod. NRZ with } \Delta f &= 1 \text{ GHz}
\end{align*}

First, the power level received at the photodetector must be higher than the receiver sensitivity to guarantee the correct performance (power budget):

(In this case, only fiber losses due to the attenuation coefficient have been considered)

\[
S (\text{dBm}) \leq P_T (\text{dBm}) - \Sigma L (\text{dB}) + G (\text{dB})
\]

\[
G \geq S (\text{dBm}) - P_T (\text{dBm}) - \Sigma L (\text{dB}) = -30 \text{ dBm} - 0 \text{ dBm} - 0.2 \text{ dB/km} \times 200 \text{ km} = 10 \text{ dB}
\]

\[
G_{\text{min}} = 10 \text{ dB}
\]

¿Any effect limiting max. amplifier gain?

Nonlinear effects: SRS and SBS

\[
P_{\text{SRS}}^{\text{threshold}} \approx 16 \frac{A_{\text{ef}}}{g_R L_{\text{ef}}} \quad P_{\text{SBS}}^{\text{threshold}} \approx \frac{42 A_{\text{ef}}}{L_{\text{ef}} g_B} \left(1 + \frac{\Delta f_o}{\Delta f_B}\right)
\]

Where effective area and length are:

\[
A_{\text{ef}} = \pi w^2 \quad l_{\text{ef}} = \frac{1 - e^{-\alpha L}}{\alpha}
\]
Lecture 4: Multi-channel Optical Systems

Optical Communication Systems and Networks

Nonlinear effects: SRS and SBS

\[ P_{SRS}^{\text{threshold}} \approx 16 \frac{A_{\text{ef}}}{g_R L_{\text{ef}}} \]

\[ P_{SBS}^{\text{threshold}} \approx \frac{42 A_{\text{ef}}}{L_{\text{ef}} g_B} \left( 1 + \frac{\Delta f_o}{\Delta f_B} \right) \]

Case 1: Booster configuration (restrictive option)

\[ \text{Pout (dBm)} = \text{Pin (dBm)} + G (\text{dB}) \leq P_{SRS \text{ or SBS threshold}} (\text{dBm}) \]

SRS or SBS threshold determines max. amplifier gain \( G_{\text{max}} \)

Assuming typical values of modal field diameter \( w = 4.5 \mu m \) and attenuation coefficient \( \alpha = 0.2 \text{ dB/km} \):

\[ A_{\text{ef}} = \pi w^2 = 63.6 \mu m \]

\[ l_{\text{ef}} = \frac{1 - e^{-\alpha L}}{\alpha} = \frac{1 - e^{-0.2*200/4.34}}{0.2/4.34} = 17.36 \text{ km} \]
Nonlinear effects: SRS and SBS

\[ P_{SRS \, \text{threshold}} \approx 16 \frac{A_{ef}}{g_R L_{ef}} \]
\[ P_{SBS \, \text{threshold}} \approx 42 A_{ef} \left( 1 + \frac{\Delta f_o}{\Delta f_B} \right) \]

Where: \( g_R = 7 \cdot 10^{-14} \text{ m/W} \), \( g_B = 4 \cdot 10^{-11} \text{ m/W} \) and \( \Delta f_B = 20 \text{ MHz} \)

\[ P_{SRS \, \text{threshold}} \approx 16 \frac{63.6 \times 10^{-12}}{7 \cdot 10^{-14} \times 17360} = 0.8375 \text{ W} = 29.23 \text{ dBm} \]

\[ P_{SBS \, \text{threshold}} \approx 42 \times 63.6 \times 10^{-12} \left( 1 + \frac{10^9}{20 \times 10^6} \right) = 98.1 \text{ mW} = 19.91 \text{ dBm} \]

Gmax (dB) = Pout (dB) - Pin (dB) = 19.91 - 0 (dB) = 19.91 dB

10 ≤ G (dB) ≤ 19.91
Parameters
\[ \lambda = 1550 \text{ nm} \quad L = 200 \text{ km} \]
\[ P_{\text{tx}} = 1 \text{ mW} = 0 \text{ dBm} \quad S = -30 \text{ dBm} \]
Codif. NRZ with \( \Delta f = 1 \text{ GHz} \)

Nonlinear effects: SRS and SBS

\[ P_{\text{SRS threshold}} \approx 16 \frac{A_{\text{ef}}}{g_R L_{\text{ef}}} \]
\[ P_{\text{SBS threshold}} \approx 42 A_{\text{ef}} \left( 1 + \frac{\Delta f_0}{\Delta f_B} \right) \]

Case 1: In-line configuration

Reduction of input power caused by fiber attenuation allows a higher amplifier gain keeping the output power below nonlinear threshold. This option is recommendable in amplified long span/links

\[ P'_{\text{in}} = \text{Pin} - \alpha \cdot \frac{L}{2} = 0 \text{ (dBm)} - 0.2 \text{ (dB/km)} \times 200/2 \text{ km} = -20 \text{ dBm} \]

\[ G_{\text{max (dB)}} = P_{\text{out (dB)}} - P'_{\text{in (dB)}} = 19.91 - (-20 \text{ (dB)}) = 39.91 \text{ dB} \]
Subcarrier Division Multiplexing (SCM)

- Access networks don’t usually carry high bit rates though the number of channels can be extremely high in many access networks (LAN and MAN)

- **Subcarrier Division Multiplexing SCM** offers the transmission capability of multiple channels simultaneously by RF subcarriers (FDM in electrical domain)

- SCM offers a huge bandwidth over the same optical carrier, providing scalability and flexibility to combine different kinds of services (format, bandwidth,...)
  Voice, data, digital audio, TV, HD-TV, video on demand...

- SCM is used to transmit RF signals over copper and fiber link in metropolitan /access networks:
  - Fiber + coper: HFC technology (Hybrid fiber-coaxial, formerly CATV networks)
  - Fiber: FTTX technologies (in particular, fiber to the home) technologies

- The resultant mux signal is directly applied to optical sources (laser or externally)
Subcarrier Division Multiplexing (SCM)

RF modulated signals multiplexed into a composite signal for providing a high-bandwidth

Configuration based on optical sources directly modulated

Service 1
Service 2
Service n

RF subcarrier 1
RF subcarrier 2
RF subcarrier n

Optical Transmitter
Optical Receiver

Signal combiner

Optical fiber link, passive optical network, ...

Electrical filtering and processing, ...

\[ P = P_0 \left( 1 + \sum_{i=1}^{n} m_i a_i \cos(2\pi f_i t + \phi_i) \right) \]

Resultant modulated signal power (intensity) at the entrance of the optical fiber
Subcarrier Division Multiplexing (SCM)

RF modulated signals multiplexed into a composite signal for providing a high-bandwidth

Configuration based on optical sources externally modulated

Optical Transmitter (CW performance)

Electro-optical modulator

Optical fiber link, passive optical network, ...

Electrical filtering and processing, ...

VCO RF subcarrier j
High Capacity Systems based on WDM - SCM

Service 1
RF subcarrier \( f_1 \)

Service 2
RF subcarrier \( f_2 \)

Service n
RF subcarrier \( f_n \)

Optical Carrier \( \lambda_1 \)

Signal combiner

Optical Carrier \( \lambda_2 \)

RF subcarrier \( f_1 \)

RF subcarrier \( f_2 \)

RF subcarrier \( f_n \)

Optical Carrier \( \lambda_n \)

Optical fiber link, passive optical network, ...

Service 1

Service 2

Service n

Optical Receiver 1
VCO
RF subcarrier \( i \)

Optical Receiver 2
VCO
RF subcarrier \( j \)

Optical Receiver n
VCO
RF subcarrier \( k \)

Electrical filtering and processing, ...

WDM Multiplexer

WDM Demultiplexer
SCM systems. Geographic reach

- Optical Splitter
- O/E converter
- FTTH (Fiber to the home)
- FTTB (Fiber to the building)
- FTTC (Fiber to the curb)

Figure based on the source: “Sistemas de Comunicaciones Ópticas”, D. Pastor, F. Ramos, J. Capmany, Ed. Servicio Publicaciones UPV, 2007
Subcarrier Division Multiplexing (SCM)

Features of transmitted signals in SCM (FTTX, HFC)

**DIGITAL SIGNALS**
- M-QAM modulation
- RF subcarriers: 550-862 MHz
- Channel Bandwidth: 6-8 MHz

**ANALOGIC SIGNALS**
- AM-VSB (catv) modulation
- RF subcarriers: 50-550 MHz
- Channel Bandwidth: 6-8 MHz

**DIGITAL SIGNAL**
- BASE BAND Format
- Bit rate limited by spectrum availability

**BASE BAND Degradation**
- BER, eyes diagram, SNR

**ANALOGICAL SIGNAL Degradation**
- Eyes diagram, SNR, CSO, CTB

**DIGITAL SIGNAL Degradation**
- BER, eyes diagram, SNR

Tema 4: Sistemas Multicanal

Figure based on the source: “Sistemas de Comunicaciones Ópticas”, D. Pastor, F. Ramos, J. Capmany, Ed. Servicio Publicaciones UPV, 2007
Example of a SCM-based network

Cable networks have been transformed from traditional clustered, one-way coaxial networks (CATV) for analog broadcasting to a fiber-based network two-way infrastructure capable to provide a wide variety of services (HFC, FTTH).
Lecture 4: Multi-channel Optical Systems

Optical Communication Systems and Networks

Optical side of the network

Electrical side of the network

Double-fiber ring (feeder network)

Local office / optical node

Single-fiber ring (distribution network)

### Frequency Plan

**PAL B/G**
- Channels: 110 PAL
- Band: 48.25 – 855.25 MHz
- Spacing: 7/8 MHz

**BK450**
- Channels: 48 PAL + 2 tones
- Band: 48.25 – 599.25 MHz
- Spacing: 7/8 MHz

**BK600**
- Channels: 110 PAL
- Band: 48.25 – 855.25 MHz
- Spacing: 7/8 MHz

**CENELEC**
- Channels: 42 PAL
- Band: 48.25 – 855.25 MHz
- Spacing: 7/8 MHz

### RF Spectrum of downlink and uplink in HFC networks

- **Internet**
- **Return channel QPSK**
- **FM**
- **Internet (TV analog)**
- **TV digital, VoD (64/256-QAM)**
- **Internet**

<table>
<thead>
<tr>
<th>f(MHz)</th>
<th>5</th>
<th>65</th>
<th>80.6</th>
<th>550</th>
<th>790</th>
<th>862</th>
</tr>
</thead>
<tbody>
<tr>
<td>uplink</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>downlink</td>
<td></td>
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</tbody>
</table>
## Impairments induced in a SCM system

<table>
<thead>
<tr>
<th>Source</th>
<th>Impairments</th>
<th>Impact on System</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>• Intensity noise (RIN)</td>
<td>• CNR</td>
<td>Use a DFB selecting a proper point of biasing and extinction ratio</td>
</tr>
<tr>
<td></td>
<td>• Nonlinear distortion</td>
<td>• CTB and CSO</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Clipping</td>
<td>• CTB and CSO</td>
<td></td>
</tr>
<tr>
<td>Receiver</td>
<td>• Thermal noise</td>
<td>• CNR</td>
<td>• Impedance matching</td>
</tr>
<tr>
<td>Fiber</td>
<td>• Dispersion (chromatic or polarization mode)</td>
<td>• No significant impact due to reduced distances</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Stimulated Brillouin Scattering (SBS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Stimulated Raman Scattering (SRS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiber amplifier</td>
<td>• Electrical segment (if exists): Nonlinear effects over RF subcarriers</td>
<td>• CTB and CSO</td>
<td>• Optimize out power and the number of cascaded amplifiers</td>
</tr>
<tr>
<td></td>
<td>• Optical segment: Signal-spontaneous and spontaneous-spontaneous induced noise and distortion</td>
<td>• CNR, CTB and CSO</td>
<td>• Filtering to reduce spontaneous-spontaneous noise</td>
</tr>
</tbody>
</table>

Table taken from the source: I. Kaminow, “Optical Fiber telecommunications”, pag. 432, Ed. Academic Press,
Evaluating SCM performance... (i)

Excluding fiber effects, the carrier to noise ratio (CNR) per channel is given by:

\[
\text{CNR} = \frac{\text{mean signal power}}{\text{noise power}} = \frac{1}{2} \left( m \Re P \right)^2 \frac{1}{\sigma_s^2 + \sigma_T^2 + \sigma_{\text{RIN}}^2 + \sigma_{\text{IMD}}^2}
\]

where:

1) **SHOT NOISE:** \[ \sigma_s^2 = 2 q (\Re P + I_d) \Delta f \] \( I_d \): dark current

2) **THERMAL NOISE:** \[ \sigma_T^2 = \frac{4 k_B T}{R_L} F_n \Delta f \] \( F_n \): preamplifier noise factor, \( R_L \): resistive load

3) **RELATIVE INTENSITY NOISE (RIN):** \[ \sigma_{\text{RIN}}^2 = (\Re P)^2 \cdot RIN \cdot \Delta f \]

- Receiver converts power fluctuations into current variations which contribute to the overall noise generated at the receiver.
- **Uniform RIN spectrum** is assumed over the receiver bandwidth (\( \Delta f \) electronic bandwidth for the channel located at subcarrier \( f_c \)).
- Currently, low RIN sources are used to limit this effect (below -160 ~ -150 dB/Hz)
Evaluating SCM performance... (ii)

Distortion caused by intermodulation products and armonic generation are generated at the following locations of a SCM system:

- **Transmitter:**
  - Static intermodulation
  - Dynamic intermodulation
  - Clipping

- **Optical fiber:**
  - Chromatic o polarization mode (PMD) dispersión
  - Chirp (Increasing of dispersion effects by directly modulated lasers)
  - Nonlinear effects arising from high input levels of optical intensity

- **Receiver:**
  - Nonlinear behaviour in photodiodes

The system performance is evaluated by the carrier to interference ratio, CIR
Evaluating SCM performance... (iii)

• The response $P-I$ ($P-V$) usually does not present a linear behaviour:

$$P=a+b·I+c·I^2+d·I^3+........... \text{ in lasers directly modulated}$$

$$P=a+b·V+c·V^2+d·V^3+...... \text{ in external modulators}$$

$c$ and $d$ are the coefficients which specify the nature of the non-linearity

• This performance is responsible for:
  
  – Harmonic distortion (AD)
  
  – Intermodulation (IM)

• Under this performance, the SCM signal will undergo a degradation by the presence of intermodulation beats:

$$\text{IMD}_2=DA_2+IM_2 \quad \text{IMD}_3=DA_3+IM_3$$
SCM Impairments: Nonlinear performance of optical sources (i)

Linear response

Nonlinear response

Laser nonlinear response changes the original wave shape (distortion)...

...and as a consequence, new frequency terms arise in the system (harmonic and intermodulation distortion are increased)
SCM Impairments: Nonlinear performance of optical surces (ii)

Nonlinear response is responsible for the change of the original wave shape (distortion)...

...and as a consequence, new frequency terms are introduced in the system (harmonic and intermodulation distortion are increased)
SCM Impairments: Harmonic and Intermodulation Distortion

2nd Order Harmonic Distortion

Input: \( I_{in} = a_0 + a_1 \cdot \sin(2\pi f_1 t) \)

Output: \( P_{out} \approx C \cdot I_{in}^2 = C \cdot [a_0 + a_1 \cdot \sin(2\pi f_1 t)]^2 = C \cdot [a_0^2 + 2a_0a_1 \cdot \sin(2\pi f_1 t) + a_1^2 \sin^2(2\pi f_1 t)] \)

Figure based on the source: “Sistemas de Comunicaciones Ópticas”, D. Pastor, F. Ramos, J. Capmany, Ed. Servicio Publicaciones UPV, 2007
SCM Impairments: Harmonic and Intermodulation Distortion

3rd Order Harmonic Distortion

Input: \( l_{in} = a_0 + a_1 \cdot \text{sen}(2\pi f_1 t) \)

Output: \[ P_{out} \approx D \cdot l_{in}^3 = D \cdot [ a_0 + a_1 \cdot \text{sen}(2\pi f_1 t) ]^3 = D \cdot [ a_0^3 + 3a_0^2a_1 \cdot \text{sen}(2\pi f_1 t) + 3a_0 a_1^2 \cdot \text{sen}^2(2\pi f_1 t) + a_1^3 \cdot \text{sen}^3(2\pi f_1 t) ] \]

Figure based on the source: “Sistemas de Comunicaciones Ópticas”, D. Pastor, F. Ramos, J. Capmany, Ed. Servicio Publicaciones UPV, 2007
SCM Impairments: Harmonic and Intermodulation Distortion

2nd Order Intermodulation Distortion

Input:
\[ I_{in} = a_0 + a_1 \cdot \text{sen}(2\pi f_1 t) + a_2 \cdot \text{sen}(2\pi f_2 t) \]

Output:
\[ P_{out} \approx C \cdot I_{in}^2 = C \cdot [a_0^2 + a_1 \cdot \text{sen}(2\pi f_1 t) + a_2 \cdot \text{sen}(2\pi f_2 t)]^2 = C \cdot [a_0^2 + 2a_0a_1 \cdot \text{sen}(2\pi f_1 t) + 2a_0a_2 \cdot \text{sen}(2\pi f_2 t) + 2a_1a_2 \cdot \text{sen}(2\pi f_1 t) \cdot \text{sen}(2\pi f_2 t) + a_1^2 \cdot \text{sen}^2(2\pi f_1 t) + a_2^2 \cdot \text{sen}^2(2\pi f_2 t)] \]

**SCM Impairments:** Harmonic and Intermodulation Distortion

### 3rd Order Intermodulation Distortion

**Input:**
\[ I_{\text{in}} = a_0 + a_1 \cdot \sin(2\pi f_1 t) + a_2 \cdot \sin(2\pi f_2 t) \]

**Output:**
\[ P_{\text{out}} \approx D \cdot I_{\text{in}}^3 = D \cdot \left[ a_0^3 + 3a_0^2a_1 \cdot \sin(2\pi f_1 t) + 3a_0^2a_2 \cdot \sin(2\pi f_2 t) + 3a_1^2a_2 \cdot \sin^2(2\pi f_1 t) \cdot \sin(2\pi f_2 t) + 3a_1a_2^2 \cdot \sin(2\pi f_1 t) \cdot \sin^2(2\pi f_2 t) + 6a_0a_1a_2 \cdot \sin(2\pi f_1 t) \cdot \sin(2\pi f_2 t) + a_1^3 \cdot \sin^3(2\pi f_1 t) + a_2^3 \cdot \sin^3(2\pi f_2 t) \right] \]

Figure based on the source: “Sistemas de Comunicaciones Ópticas”, D. Pastor, F. Ramos, J. Capmany, Ed. Servicio Publicaciones UPV, 2007
**SCM Impairments: Harmonic and Intermodulation Distortion**

- **Second-order distortion, CSO:** Composite second order intermodulation distortion

CSO is defined as the ratio between power corresponding to the largest number of second-order intermodulation beats and the subcarrier power $C$:

$$CSO = 10 \log_{10}(N_{CSO}(cm)^2)$$

$$N_{CSO} = N(N - 1)$$ where $N$ is the number of RF channels

To guarantee acceptable quality of service (QoS), the CSO values should be higher than 53dBc at the consumer premises.

Lower values of CNR in that RF channel will be manifested as a “snow” phenomenon.
**SCM Impairments:** Harmonic and Intermodulation Distortion

- **3rd-order distortion, CTB:** Composite triple beat intermodulation distortion

CTB is defined as the ratio between power corresponding to the largest number of third-order intermodulation beats and the subcarrier power $C$:

$$CTB = 10 \log_{10} \left( N_{CTB} \left( \frac{3}{2} dm^2 \right)^2 \right)$$

where $N_{CTB} = N(N - 1)(N - 2)/2$

$N$ is the number of RF channels
SCM Impairments: Harmonic and Intermodulation Distortion

Impairments produced by intermodulation distortion depends on the following factors:

• Number of second and third intermodulation and harmonic distortion products
  
  – Generated tones can fall inside the information channels band by causing interferences and noise.

• Spectral spacing between RF subcarriers
  
  – CSO and CTB values are normalized to the carrier power level and they are referred as dBc units (where “c” denotes the dB value with regard to the carrier)
  
  – CSO and CTB values below -60 dBc are considered negligible on the system performance. However these values can rapidly grow as subcarrier modulation indexes $m$ are increased.

  Typical values:  \( \text{CSO}<-52 \, \text{dBc} \quad \text{CTB}<-52 \, \text{dBc} \)

DYNAMIC INTERMODULATION

• It appears in laser-diode type transmitters operating under direct current modulation as a result of a nonlinear dependence between carriers and photons in the region where laser emission is produced
SCM Impairments: Clipping

The optical power emission is negligible when diode laser is driven below its threshold.

- Clipping of the signal when the laser is directly modulated in intensity
  The resultant signal contains new frequency terms (it is not exactly the original) which also participate in intermodulation beats

- Additional distortion can be also produced as a result of relaxation oscillations
SCM Impairments: Subcarrier suppression

Dispersion effects
- Phase changes induced along the optical link by chromatic dispersion are responsible for the elimination of RF components in the detection process.

![Diagram showing optical and electrical spectra with subcarrier suppression and phase reversal effects.](image-url)
SCM Impairments: Subcarrier suppression

Dispersion effects

- Phase changes induced along the optical link by chromatic dispersion are responsible for the elimination of RF components in the detection process.

\[
\frac{1}{2} \cos ((\omega_p - \omega_m)t + \theta) \quad \frac{1}{2} \cos ((\omega_p + \omega_m)t + \theta) \\
\cos (\omega_p t + \theta)
\]